White paper: Exploring planet Earth as a unified dynamic system

Strategic focus areas: 8. Exploration of the dynamic Earth system

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The Earth can be viewed as a unified system of certain physical variables. Based on fundamental physics, there is conservation of, angular momentum, linear momentum, mass for the whole planet if interactions of these variables from the region outside the Earth does not occur. If such interaction does occur (as in the case of lunar tides, for example) then knowledge of the amount into and out of the system is important as well.

In the case of *angular momentum*, the solid Earth (crust + mantle) exchanges that quantity with the geophysical fluids that surround it; such fluctuations occur on a broad range of timescales. Variations in the geophysical fluids, namely the atmosphere, oceans, hydrological fluids on the surface of the Earth, and the liquid core, and even the viscous mantle (though very slowly) change their angular momentum, so that the solid Earth absorbs it and changes its rotation accordingly. Fluctuations of the angular momentum in the axial direction will change the rotation rate of the solid Earth and those in the equatorial direction will change the motions of the pole, also known as Earth wobble. In both cases, the orientation of the Earth will fluctuate. This orientation information is important for the purposes of understanding the Earth's internal geophysics and for external frame of reference issues. As examples of each, knowledge of the Earth's orientation and the fluid angular momentum has been used to understand the internal composition and properties such as elasticity of the Earth, and for precise navigation corrections in NASA planetary missions. The angular momentum also is an index of weather and climate fluctuations on many time scales, from the subdiurnal, to the subseasonal, Madden-Julian scale, to the seasonal, to interannual, including having the impact of both the quasi-biennial oscillation and the El-Nino. Thus these various signatures actually have an impact on the Earth's rotation vector. Fluctuations of the solar cycle also impact the Earth rotation signal in part.

The torque necessary to dynamically effect the angular momentum transfer from one geophysical component to another is also of interest to understand the whole Earth system. An atmospheric pressure-gradient force acting normally across variable topography will cause a "mountain torque," dominating at frequencies higher than sub-seasonal, reflecting synoptic weather forcing on Earth rotation. On lower frequencies it has about the same variance as the other principal torque, that causing by tangential forces along the Earth's surface.

How the components of the Earth's dynamic system are measured and therefore explored requires various space-based and other instrumentation. The Earth's rotation and hence the angular momentum of the solid Earth is a combination of Global Positioning System, VLBI (Very Long Baseline Interferometry), and Satellite Laser Ranging techniques. VLBI itself is a complex technology involving measurements from remote radio sources in the distant universe, as well as tracking signals dependent upon tropospheric moisture, ionospheric interactions, and other effects.

The atmospheric angular momentum is explored through the heteorogenous observations that are assimilated into global atmospheric models. Such observables assimilated into the weather models are infrared and microwave-based satellite instrument measurements, aircraft- and in situ radiosonde-based data. The models are critical tools in our understanding of atmospheric fluctuations, in weather forecasting and in making future assessments based upon changing climate scenarios.

Determining the ocean contribution to the angular momentum problem also involves space-based observations, including altimetry, and active and passive microwave sensing of the surface to determine the air-sea stresses. All this information is used with ocean models in large-scale efforts to determine state of the ocean and its angular momentum.

Parallel to the angular momentum balance in the terrestrial system, is *linear momentum*. Linear momentum changes in the whole Earth appears to be forced by changes in the geophysical fluids. Understanding and measuring this result will be relevant to reference frames of the Earth, namely, fluctuations of the geocenter, important as the origin of the terrestrial reference frame.

Mass is exchanged between components in the case of water substance, but it is also redistributed within components. Thus fluctuations in the hydrology of the planet may occur from one part of the ocean to another, into or out of the atmosphere, or hydrological reservoirs. Atmospheric (dry air) pressure variations are themselves mass redistributions. Space-based measurements of the Earth's fluctuating gravity field help those concerned with these mass variations. The GRACE satellite system is the latest such US satellite (pair) to measure such gravity field fluctuations.

Thus, we encourage the investigation and exploration of the Earth's dynamic system, including the angular momentum/Earth rotation; linear momentum/geocenter, and mass/time-variable gravity focus areas as well as the dynamic connections between components in each of the areas. The importance of this investigation area to human activity are several-fold: it involves the understanding of the Earth's interior properties, related to possible geophysical Earth hazards, it help in diagnosing information about atmosphere and ocean models, and it is important in many other applications, and practical information about the Earth's reference frames, including navigation. Such accurate navigation requirements, moreover, are necessary to send exploratory missions to the planets of the solar system.

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